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FOR

DEPOSITION METHOD FOR NANOSTRUCUTURE MATERIALS

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DEPOSITION METHOD FOR NANOSTRUCTURE MATERIALS

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At least some aspects of this invention were made with Government support under contract no. N00014-98-1-05907. The Government may have certain rights in this invention.

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FIELD OF THE INVENTION

The present invention relates to methods of depositing a nanostructure or nanotube-containing material onto a substrate, and associated structures and devices.

BACKGROUND OF THE INVENTION

In the description of the background of the present invention that follows reference is made to certain structures and methods, however, such references should not necessarily be construed as an admission that these structures and methods qualify as prior art under the applicable statutory provisions. Applicants reserve the right to demonstrate that any of the referenced subject matter does not constitute prior art with regard to the present invention.

The term "nanostructure" material is used by those familiar with the art to designate materials including nanoparticles such as C_{60} fullerenes, fullerene-type concentric graphitic particles; nanowires/nanorods such as Si, Ge, SiO_x, GeO_x, or nanotubes composed of either single or multiple elements such as carbon, B_xN_y, $C_xB_yN_z$, MoS_2, and WS_2. One of the common features of nanostructure materials is their basic building blocks. A single nanoparticle or a carbon nanotube has a dimension that is less than 500 nm at least in one direction. These types of materials have been shown to exhibit certain properties that have raised interest in a variety of applications and processes.

U.S. Patent No. 6,280,697 to Zhou et al. (entitled "Nanotube-Based High Energy Material and Method"), the disclosure of which is incorporated herein by reference, in its entirety, discloses the fabrication of carbon-based nanotube materials and their use as a battery electrode material.

U.S. Patent No. ____________ (Serial No. 09/296,572 entitled "Device Comprising Carbon Nanotube Field Emitter Structure and Process for Forming Device") the disclosure of which is incorporated herein by reference, in its entirety, discloses a carbon nanotube-based electron emitter structure.

U.S. Patent No. ____________ (Serial No. 09/351,537 entitled "Device Comprising Thin Film Carbon Nanotube Electron Field Emitter Structure"), the disclosure of which is incorporated herein by reference, in its entirety, discloses a carbon-nanotube field emitter structure having a high emitted current density.

U.S. Patent No. 6,277,318 to Bower et al. (entitled "Method for Fabrication of Patterned Carbon Nanotube Films"), the disclosure of which is incorporated herein by reference, in its entirety, discloses a method of fabricating adherent, patterned carbon nanotube films onto a substrate.

U.S. Patent No. _____________ (Serial No. 09/594,844 entitled "Nanostructure-Based High Energy Material and Method"), the disclosure of which is incorporated herein by reference, in its entirety, discloses a nanostructure alloy with alkali metal as one of the components. Such materials are described as being useful in certain battery applications.

U.S. Patent No. _______________ (Serial No. 09/679,303 entitled "X-Ray Generating Mechanism Using Electron Field Emission Cathode"), the disclosure of which is incorporated herein by reference, in its entirety, discloses an X-ray generating device incorporating a nanostructure-containing material.

U.S. Patent No. _____________ (Serial No. 09/817,164 entitled "Coated Electrode With Enhanced Electron Emission And Ignition Characteristics") the disclosure of which is incorporated herein by reference, in its entirety, discloses an electrode including a first electrode material, an adhesion-promoting layer, and a carbon nanotube-containing material disposed on at least a portion of the adhesion promoting layer, as well as associated devices incorporating such an electrode.

U.S. Patent No. _____________ (Serial No. 09/881,684 entitled "Method of Making Nanotube-Based Material With Enhanced Field Emission") the disclosure of which is incorporated herein by reference, in its entirety, discloses a technique for introducing a foreign species into the nanotube-based material in order to improve the emission properties thereof.

As evidenced by the above, nanostructure materials, such as carbon nanotubes possess promising properties, such as electron field emission characteristics which appear to be far superior to that of conventional field emitting materials. In particular, carbon-nanotube materials exhibit low emission threshold fields as well as large emission current densities. Such properties make them attractive for a variety of microelectronic applications, such as lighting elements, field emission flat panel displays, gas discharge tubes for over voltage protection, and x-ray generating devices.

However, the effective incorporation of such materials into these devices has been hindered by difficulties encountered in the processing of such materials. For instance, carbon nanotubes are produced by techniques such as laser ablation and arc discharge methods. Carbon nanotubes produced by such techniques are collected, subjected to further processes (e.g. - filtration and/or purification) and subsequently deposited or otherwise incorporated into the desired device. Thus, according to these conventional techniques, it is not possible to directly form carbon nanotubes onto a substrate or carrier material.

Post-formation methods such as screen printing and spraying have been utilized to deposit pre-formed carbon nanotubes on a substrate. However, such techniques pose certain drawbacks. For instance, screen printing requires the use of binder materials as well as an activation step. Spraying can be inefficient and is not practical for large-scale fabrication.

Carbon nanotubes have been grown directly upon substrates by use of chemical vapor deposition (CVD) techniques. However, such techniques require relatively high temperatures (e.g. - 600-1,000°C) as well as reactive environments in order to effectively grow the nanotubes. The requirement for such harsh environmental conditions severely limits the types of substrate materials which can be utilized. In addition, the CVD technique often results in mutli-wall carbon nanotubes. These mutli-wall carbon nanotubes generally do not have the same level of structural perfection and thus have inferior electronic emission properties when compared with single-walled carbon nanotubes.

Thus, there is a need in the art to address the above-mentioned disadvantages, and others, associated with conventional fabrication techniques.

SUMMARY OF THE INVENTION

The present invention addresses the above-mentioned disadvantages associated with the state of the art, and others.

For example, the present invention provides a process for depositing pre-formed nanostructure material, such as carbon nanotubes, onto a substrate material utilizing electrophoretic deposition.

According to one embodiment, the present invention provides a method of depositing a nanostructure-containing material onto a substrate, the method comprising:

(i) forming a suspension of pre-formed nanostructure-containing material in a liquid medium;

(ii) selectively adding one or more chemicals ("chargers") to the liquid medium;

(iii) immersing two electrodes in the suspension, wherein at least one of the electrodes comprises the substrate; and

(iv) applying a direct or alternating current to the immersed electrodes thereby creating an electrical field between the electrodes;

whereby the nanostructure-containing material is caused to migrate toward, and attach to, the substrate.

According to another embodiment, the present invention provides a method of attaching a single nanotube or nanowire onto a sharp tip of a sharp object, the method comprising:

(i) forming a suspension of pre-formed nanostructure-containing material in a liquid medium;

(ii) selectively adding a charger to the liquid medium;

(iii) immersing at least one electrode in the suspension;

(iv) placing the sharp tip directly above the surface of the suspension and on a stage where the tip can be moved closer or further away from the surface of the suspension; and

(v) applying a direct or alternating current to the immersed electrode and the sharp object and electrically connecting a current meter to the sharp tip.

According to yet another embodiment, the present invention provides a method of depositing a nanostructure-containing multi-layer structure onto substrate, the method comprising:

(i) providing a multilayer structure comprising a substrate and a plurality of additional layers disposed on the substrate;

(ii) providing a plurality of exposed areas on a surface of the substrate;

(iii) forming a suspension of pre-formed nanostructure-containing material in a liquid medium;

(iv) selectively adding a charger to the liquid medium;

(v) immersing at least one electrode and the multilayer structure in the suspension;

(vi) applying a direct or alternating current to the electrode and the multilayer structure thereby creating an electrical field therebetween;

whereby the nanostructure-containing material is caused to migrate toward, and attach to, the exposed areas on the substrate.

According to another embodiment, the present invention provides a method of depositing a pattern of nanostructure-containing material onto a substrate, the method comprising:

(i) providing a substrate having a first surface with a mask disposed thereon, the mask having openings through which areas of the first surface are exposed;

(ii) forming a suspension of pre-formed nanostructure-containing material in a liquid medium;

(iii) selectively adding a charger to the liquid medium;

(iv) immersing at least one electrode and the masked substrate in the suspension;

(v) applying a direct or alternating current to the electrode and the masked substrate thereby creating an electrical field therebetween;

whereby the nanostructure-containing material is caused to migrate toward, and attach to, those exposed areas on the first surface of the substrate; and

(vi) removing the mask.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

Fig. 1A is a transmission electron microscopic (TEM) image of purified single walled carbon nanotube bundles.

Fig. 1B is a TEM image of single walled carbon nanotubes etched to a 4 micron average bundle length.

Fig. 1C is a TEM image of single walled carbon nanotubes etched to a 0.5 micron average bundle length.

Fig. 2 is a schematic illustration of an electrophoretic deposition process according to the principles of the present invention.

Fig. 3A is a scanning electron microscope (SEM) image of a coating of "long" single-walled carbon nanotubes onto a substrate according to the principles of the present invention.

Fig. 3B is a SEM image of a coating of "short" single-walled carbon nanotubes onto a substrate according to the principles of the present invention.

Fig. 4 is a plot of the measured electron field emission current versus the applied electrical field from a single-wall carbon nanotube films formed by the process of the present invention.

Fig. 5A is a schematic illustration of a process according to the present invention used to attach a bundle or a single carbon nanotube or a nanowire to an object with a sharp tip.

Fig. 5B is a schematic illustration of the sharp tip having an attached single carbon nanotube or nanowire formed according to a process as depicted in Fig. 5A.

Fig. 5C is an SEM image the sharp tip having an attached single carbon nanotube or nanowire formed according to a process of the present invention.

Fig. 6A-6C are a schematic illustrations of a selective deposition process performed according to the present invention.

Figs. 7A and 7B are SEM images showing a top view of a coated surface of a multi-layer structure formed according to a selective deposition process as illustrated in Figs. 6A-6C.

Figures 8A-8C are schematic illustrations of an embodiment of a selective deposition process according to the present invention.

Figure 8D is a side view of an embodiment of a patterned substrate formed according to the process of Figures 8A-8C.

DETAILED DESCRIPTION OF THE INVENTION

A method performed consistent with the principles of the present invention, and according to a preferred embodiment, along with corresponding structures and devices, are described as follows.

Generally, a method performed according to the principles of the present invention can include a combination of some or all of the following steps: (1) forming a solution or suspension containing the nanostructure material; (2) selectively adding "chargers" to the solution; (3) immersing electrodes in the solution, the substrate upon which the nanostructure material is to be deposited acting as one of the electrodes; (4) applying a direct and/or alternating current thus creating an electrical field between the electrodes for a certain period of time thereby causing the nanostructure materials in the solution to migrate toward and attach themselves to the substrate electrode; and (5) optional subsequent processing of the coated substrate.

The process begins with pre-formed raw nanostructure or nanotube-containing material, such as a carbon nanotube-containing material. This raw nanotube material can comprise at least one of single-walled carbon nanotubes and multi-walled carbon nanotubes. According to a preferred embodiment, the raw carbon nanotube-containing material comprises single-walled carbon nanotubes.

The raw carbon-containing material can be fabricated according to a number of different techniques familiar to those in the art. For example, the raw carbon nanotube-containing material can be fabricated by laser ablation techniques (e.g. - see U.S. Patent No. 6,280,697), chemical vapor deposition techniques (see, e.g. - C. Bower et al., "Plasma Induced Conformal Alignment of Carbon Nanotubes on Curvatured Surfaces," Appl Phys Lett. Vol. 77, No. 6, pgs. 830-32 (2000)), or arc-discharge techniques (see, e.g. - C. Journet et al., Nature, Vol. 388, p. 756 (1997)).

It is also contemplated by the present invention that raw materials be in the form of nanotube structures with a composition of $B_xC_yN_z$ (B= boron, C= carbon, and N=nitrogen), or nanotube or concentric fullerene structures with a composition MS_2 (M= tungsten, molybdenum, or vanadium oxide) can be

utilized. These raw materials can be formed by any suitable technique, such as the above-mentioned arc-discharge technique.

It is also within the scope of the present invention that the raw materials are in the form of nanowires with at least one of the following: elemental metal, Si, Ge, oxide, carbide, nitride, chalcogenide. In addition, the raw materials can be in the form of nanoparticles of elemental metal, metal oxide, elemental and compound semiconducting materials.

Next, the raw carbon nanotube-containing material is subjected to purification. A number of techniques for purifying the raw materials are envisioned. According to one preferred embodiment, the raw material can be purified by reflux in a suitable solvent, such as a combination of peroxide (H_2O_2) and water, with an H_2O_2 concentration of 1-40% by volume, preferably about 20% by volume H_2O_2, with subsequent rinsing in CS_2 and then in methanol, followed by filtration. According to an exemplary technique, approximately 10-100 ml of peroxide is introduced into the medium for every 1-10 mg of nanotubes in the medium, and the reflux reaction is carried out at a temperature of 20-100°C (see, e.g. - U.S. Patent No. ___________ (Serial No. 09/679,303)).

According to another alternative, the raw carbon nanotube-containing material is placed in a suitable liquid medium, such as an acidic medium, an organic solvent, or an alcohol, preferably methanol. The nanotubes are kept in suspension within the liquid medium for several hours using a high-powered ultrasonic horn, while the suspension is passed through a microporous membrane. In another embodiment, the raw materials can be purified by oxidation in air or an oxygen environment at a temperature of 200-700°C. The impurities in the raw materials are oxidized at a faster rate than the nanotubes.

In yet another embodiment, the raw materials can be purified by liquid chromatography to separate the nanotubes/nanowires from the impurities.

The raw material is then optionally subjected to further processing to shorten the nanotubes and nanotube bundles, such as chemical etching.

According to one embodiment, the purified carbon nanotube material can be subjected to oxidation in a strong acid. For instance, purified carbon nanotube

material can be placed in an appropriate container in a solution of acid comprising H_2SO_4 and HNO_3. The carbon nanotubes in solution are then subjected to sonication for an appropriate length of time. After sonication, the processed nanotubes are collected from the acid solution by either filtration or centrifuging after repeated dilution with de-ionized water.

An illustrative example of such a process is described as follows. Purified raw material formed as described above was found to contain approximately 90% single-walled nanotube bundles over 10μm in length and 5-50 nm in bundle diameter. Such "long" nanotube bundles are illustrated by Fig. 1A. This material was chemically etched in a solution of H_2SO_4 and HNO_3 for 10-24 hours while being subjected to ultrasonic energy. After etching the single wall carbon nanotube bundles etched for 20 hours had an average length of 4μm and the single wall carbon nanotube bundles etched for 24 hours had an average bundle length of 0.5μm, as shown by the transmission electron microscopy images in Figures 1B – 1C. Alternatively, the purified materials can be chemically functionalized by, for example, chemically or physically attaching chemical species to the outer surfaces of the carbon nanotubes such that they will be either soluble or form stable suspensions in certain solvents.

According to another alternative, the purified raw material can be shortened by mechanical milling. According to this technique, a sample of the purified carbon nanotube material is placed inside a suitable container, along with appropriate milling media. The container is then shut and placed within a suitable holder of a ball-milling machine. According to the present invention, the time that the sample is milled can vary. An appropriate amount of milling time can be readily determined by inspection of the milled nanotubes.

Regardless of the technique utilized, the preferred length of the shortened material, such as the above-mentioned nanotubes and nanotube bundles, is approximately .1-100 micrometers, preferably .1-10 micrometers, and more preferably .3-3.0 micormeters.

The purified raw material, regardless of whether subjected to the above-described shortening process, can also optionally be annealed at a suitable

temperature, such as 100°C-1200°C. According to a preferred embodiment, the annealing temperature is 100°C-600°C. The material is annealed for a suitable time period, such as approximately 1 to 60 minutes. According to a preferred embodiment, the material is annealed for approximately 1 hour. The material is annealed in a vacuum of about 10^{-2} torr, or at an even higher vacuum pressure. According to a preferred embodiment, the vacuum is about 5 x 10^{-7}torr.

The above described "raw" or pre-formed material can now be introduced into a solution for deposition onto a substrate.

A suitable liquid medium is selected which will permit the formation of a stable suspension of the raw nanostructure material therein. According to a preferred embodiment the liquid medium comprises at least one of water, methanol, ethanol, alcohol, and dimethylformamide (DMF). According to a further preferred embodiment, the liquid medium comprises ethanol. Upon adding the raw material to the liquid medium, the mixture can optionally be subjected to ultrasonic energy or stirring using, for example, a magnetic stirrer bar, in order to facilitate the formation of a stable suspension. The amount of time that the ultrasonic energy is applied can vary, but it has been found that approximately two hours at room temperature is sufficient.

The concentration of raw material in the liquid medium can be varied, so long as a stable suspension is formed. For example, with a liquid medium comprising methanol, approximately 0.01mg of the raw material, such as single-walled carbon nanotubes, can be present per ml of the liquid medium (0.01mg/ml) and provide a stable suspension. When the liquid medium comprises DMF, approximately 0.4-0.5 mg of the raw material, such as single-walled carbon nanotubes, can be present per ml of the liquid medium (0.4-0.5mg/ml) and provide a stable suspension. When shortened carbon nanotubes are used, stable suspension can be obtained at a higher concentration. For example, a stable dispersion of approximately 0.1mg/ml of shortened nanotubes in water can be formed.

According to a preferred embodiment, a "charger" is added to the suspension in order to facilitate electrophoretic deposition. One such preferred charger is $MgCl_2$. Some other chargers include $Mg(NO_3)_2$, $La(NO_3)_3$, $Y(NO_3)_3$,

$AlCl_3$, and sodium hydroxide. Any suitable amount can be utilized. Amounts ranging from less than 1% up to 50%, by weight, as measured relative top to the amount of nanostructure-containing material, are feasible. According to a preferred embodiment, the suspension can contain less than 1% of the charger.

A plurality of electrodes are then introduced into the suspension. According to a preferred embodiment, two electrodes are utilized. One of the electrodes comprises the substrate upon which the nanostructure material is to be deposited. Any suitable substrate material is envisioned, so long as it possesses the requisite degree of electrical conductivity. According to a preferred embodiment, the substrate is either metal or doped silicon.

An alternating current, or a direct current is applied to the electrodes thereby producing an electrical field between the electrodes. This causes the nanotstructure material in the suspension to migrate toward and attach to the substrate electrode. According to one embodiment, the electrical field applied between electrodes is 0.1-1000 V/cm, and a direct current of 0.1-200 mA/cm^2 is applied for 1 second – 1 hour.

Figure 2 is a schematic illustration of the above-described process. As illustrated in Figure 2, a pair of electrodes E_1 and E_2 are introduced into the suspension S_{susp}. The electrodes E_1 and E_2 are connected to a power supply P, which produces an electrical field between E_1 and E_2. Depending on the charge of the nanostructure material contained in the suspension S_{susp}, the nanostructure material will migrate toward and attach to one of the electrodes thereby forming a coating C of the nanostructure material on one of the electrodes. In the illustrative example, the substrate S_{sub} is the negative electrode E_1, or anode.

According to a preferred embodiment, the above-described electrophoretic deposition is carried out at room temperature.

The rate of deposition of the coating C, as well as its structure and morphology can be influenced by many factors. Such factors include: the concentration of nanostructure material in the suspension S_{susp}, the concentration of the charger material (e.g. – $MgCl_2$) in the suspension S_{susp}, the conductivity of the substrate, and control of the power source P.

By way of illustration, a stainless steel substrate/electrode and a counter electrode were introduced into a suspension comprising DMF and single-walled carbon nanotubes at a concentration of 0.4mg/ml, and $MgCl_2$. A direct current was applied resulting in an electrical field of approximately 20 V/cm formed between the electrodes. Application of the current for about 30 seconds results in the formation of a smooth film of single-walled carbon nanotubes on the substrate. After application of direct current for approximately 10 minutes, a thin film of single-walled carbon nanotubes approximately 1micrometer thick was deposited on the substrate. This film was examined using a scanning electron microscope, and is illustrated in Figure 3A. The morphology of the deposited coating or film is similar to that of coating or film applied by spraying, and comprises clearly defined single-walled carbon nanotube bundles.

Figure 3B is a SEM image of a coating of single-walled carbon nanotube bundles deposited by electrophoretic deposition in the manner described above. However, the nanotubes were subjected to a previously described process to shorten their length (e.g. - to about a 0.5μm average bundle length). The film depicted in Figure 3 was densified by sintering in vacuum at a suitable temperature (e.g. - 800°C). This coating comprises distinct grain boundaries with densely packed grains. Individual single-walled carbon nanotube bundles are no longer discernable.

The particular electrode (i.e. - anode or the cathode) to which the nanostructure material migrates can be controlled through the selection of the charger material. For example, the use of a "negative" charger, such as sodium hydroxide (NaOH) imparts a negative charge to the nanostructure material, thereby creating a tendency for the nanostructure material to migrate towards the positive electrode (cathode). Conversely, when a "positive" charger material is used, such as $MgCl_2$, a positive charge is imparted to the nanostructure material, thereby creating a tendency for the nanostructure material to migrate toward the negative electrode (anode).

The electrodes are removed from the suspension after a suitable deposition period. The coated substrate electrode may optionally be subjected to further

processing. For example, the coated substrate may be annealed to remove the liquid medium. Such an annealing procedure may be preferable, since removal of impurities such as residual suspension medium improves the emission characteristics of the nanostructure material. By way of example, the coated substrate can be heated to a temperature of approximately 100-1200°C for approximately 1 hour, and then at approximately 800°C for 2 hours, both at a vacuum of approximately 5 x 10^{-7} torr.

The emission characteristics of a film of single-walled carbon nanotubes (SWNT) formed according to the present invention has been evaluated and compared to that of SWNT materials prepared by other techniques. The results are summarized in following table.

In the following table, the measurements were made using a constant DC voltage. The threshold field is defined as the electrical field required for the emission current density to reach 0.01 mA/cm^2. The current decay is calculated by $(I_{initial}-I_{final})/I_{initial}$, where $I_{initial}$ is the initial emission current and I_{final} is the emission current after 10 h of measurement.

Materials	Threshold field [V/micrometer]	Initial emission current density [mA/cm^2]	Emission current decay after 10 hours [%]
As-grown SWNT mat	1.3	200	50
Purified SWNT paper (made by filtration)	1.0	93	40
CVD SWNT film [a]	3.1	10	79
EPD long SWNT film	1.4	83	3

Fig. 4 is a plot of the total electron field emission current versus applied voltage for two samples of nanotube films A and B. Sample A was formed as previously described, using methanol as a suspension media. Sample B was formed using DMF as a suspension media. For both samples, the measurements were made over a 6mm^2 emissions area at a cathode-anode distance of 160μm at a

base pressure of $2x10^{-7}$ torr. The inset portion of Fig. 4 represents the same data plotted as I/V^2 versus I/V, which shows a substantially linear behavior which is indicative of field emission of electrons.

According to the present invention, a film is formed having a threshold field for emission of less than 1.5 volts/micrometer. The film can produce an emission current density greater than 1 A/cm^2. The film can produce a total emission current greater than 10 mA over a 6 mm^2 area. The film can also produce a pulsed emission current having a pulse frequency higher than 10 KHz, preferably higher than 100KHz. The total pulsed current measured over a 6 mm^2 area is preferably higher than 10 mA at 10-12 V/μm. Moreover, the emission current is capable of being consistently reproduced, without decay, even after a number of pulsed emissions, as evidenced by the above data. For instance, the pulsed current is stable and higher than 10mA over a 6 mm^2 area for at least 1,000 pulses, preferably for at least 10,000 pulses.

As apparent from the above, the single-walled carbon nanotube film formed according to the principles of the present invention exhibit excellent field emission characteristics, especially in the area of resistance to emission current density decay.

The coating of nanostructure materials deposited according to the principles of the present invention exhibit better adhesion that a similar coatings applied by other techniques such as spraying. While not wishing to be limited by any particular theory, the improved adhesion may be due to the formation of metal hydroxide on the surface of the substrate (formed from metal ions of the electrode and OH groups from the charger). The films formed according to the principles of the present invention also exhibit improved field emission stability (i.e. - higher resistance to field emission decay).

According to a further embodiment, the adhesion of nanotubes to the substrate can be further improved by incorporation of adhesion promoting materials such as binders, carbon-dissolving or carbide-forming metal and high temperature annealing. These materials can be introduced by, for example, one of the following processes: co-deposition of the nanostructures and particles of

adhesion promoting materials, sequential deposition, pre-deposition of a layer of adhesion promoting materials, etc.

In one embodiment, binders such as polymer binders are added to the suspension of the nanostructure-containing material which is then either stirred or sonicated to obtain a uniform suspension. Suitable polymer binders include poly(vinyl butyral-co vinyl alcohol-co-vinyl acetate) and poly(vinylidene fluoride). Suitable chargers are chosen such that under the applied electrical field, either DC or AC, the binder and the nanostructures would migrate to the same electrodes to form a coating with an intimate mixing of the nanostructures and the binder.

In another embodiment, small metal particles such as titanium, iron, lead, tin, cobalt are mixed into the suspension of the nanostructure-containing material. Suitable chargers are chosen such that under the applied electrical field, the metal particles and the nanostructures will migrate to the desired electrode to form a uniform coating with an intimate mixing of the metal particles and the nanostructures. After deposition, the coated substrate is annealed in vacuum with a base vacuum pressure of 10^{-3} torr or greater for 0.1-10 hours. Preferably, the diameter of the particles is smaller than 1 micrometer.

The binders or adhesion promoting materials can be added in any suitable amount. Amounts ranging from 0.1-20 % by weight, measured relative to the amount of nanostructure-containing material is envisioned.

In another embodiment, the substrate to be coated with the nanostructures is first coated with at least one layer of adhesion-promoting metal such as titanium, iron, lead, tin, cobalt, nickel, tantalum, tungsten, niobium, zirconium, vanadium, chromium or hafnium. The layer can be applied by techniques such as electrochemical plating, thermal evaporation, sputtering or pulsed laser deposition. After electrophoretic deposition of the nanostructures, the film is annealed in vacuum with a base vacuum pressure of 10^{-3} torr or greater for 0.1-10 hours.

Thus, the above-described processes are advantageously well-adapted for high output and automation. These processes are very versatile and can be used to form uniform coatings of various thicknesses (e.g. - tens of nanometers to a few micrometers thick), coatings on complex shapes, as well as complicated structures

such as composites and "gated" electrodes. The methods of the present invention are useful in producing nanotube materials which have properties that make them beneficial for use in a number of different applications. Generally, the method of the present invention is especially beneficial in providing nanotube material for incorporation into electron field emission cathodes for devices such as x-ray generating devices, gas discharge tubes, lighting devices, microwave power amplifiers, ion guns, electron beam lithography devices, high energy accelerators, free electron lasers, electron microscopes and microprobes, and flat panel displays.

The electrophoresis method of the present invention can used to coat substrates with composite layers in which nanostructured materials serve as one of the components. It can also be utilized to form multilayered structures on a supporting surface.

To deposit a composite layer containing nanostructure-containing material on a substrate, nanostructured materials and at least one more component (e.g. - polymer or metal particles) are suspended in a liquid medium to make up the electrophoresis bath. After selectively adding a “charger” to the suspension, two electrodes, wherein at least one of the electrodes comprises the substrate, are immersed in the suspension and a direct or alternating current is applied to the immersed electrodes thereby creating an electrical field between the electrodes. Because the nanostructured materials and the other component in the suspension are charged by the same “charger”, they would migrate toward and attach to the same substrate simultaneously under the same electrical field. In the above described method, the composition of deposited composite layer is mostly decided by the composition of the suspension in which the electrophoresis has been carried out. Therefore, composite layers having different composition can be readily obtained by immersing a substrate in baths with deferent compositions and performing the above-described electrophoretic deposition.

While a composite layer can be made by electrophoresis using only one bath, multiple baths can be used to produce a multilayered electrophoretic deposition. The electrophoresis is carried out in each bath sequentially with each

bath producing a layer of different composition in the multilayered structure. When the desired thickness of a layer is reached, the deposition electrode can be moved to the next suspension for deposition of the next layer.

The electrophoretic deposition technique disclosed can be further applied to deposit an individual or a bundle of carbon nanotubes or nanowires selectively onto a sharp tip. This sharp tip can be, for example, the tip used for microscopes including atomic force microscopes, scanning tunneling microscopes, or profilometers.

One such embodiment is illustrated in Figs. 5A-5B, where a dilute suspension of nanotube or nanowire is first prepared. A counter electrode 510 is first immersed into the suspension 520. The metal tip 530 is used as the second electrode. It is first placed perpendicular to the suspension surface with the sharp tip, where the nanotube/nanowire is to be deposited, just slightly above the top surface of the suspension. The tip is then gradually moved towards the surface of the suspension. A meter such as a current meter 540 is used to monitor the electrical current between the counter electrode and the metal tip. In addition, an appropriate optical magnification device can be used to monitor the gap between the metal tip 530 and the suspension surface 520. When the tip touches the surface of the suspension, the electrical current passing between the two electrodes is detected by the meter 540. Depending on the concentration of the nanostructures in the suspension and the electrical field used, the tip 530 is allowed to stay in contact with for a pre-determined time. The voltage applied between the two electrodes is then turned off and the tip 530 is raised to be above the suspension to stop the deposition process. The metal tip 530 with a carbon nanotube 550 or other nanostructure attached to is vacuum annealed to increase the bonding between the tip and the nanostructure. Figure 5C is an SEM image of a sharp tip having a single nanotube or nanowire deposited thereon according to the techniques of the present invention.

Another application of the process of the present invention is fabrication of triode-type structures with nanostructured field emission materials deposited in

selected areas. Such structures can be used, for example, in field emission flat panel displays; cold cathodes for x-ray tubes, microwave amplifiers, etc.

In one embodiment of this application is illustrated in Figs. 6A-7B, where a multilayer structure comprising a Si substrate 610, a dielectric insulating layer 620 such as silicon dioxide, a conducting layer 630 and a layer of photoresist 640 is fabricated by common thin film fabrication techniques (Fig. 6A). A photo-mask is used to selectively expose the photoresist 640 to ultraviolet light. The multilayer structure is then developed using suitable chemicals to remove the exposed underlying multi-layer structure at the desired locations (Fig. 6B). As illustrated in Fig. 6B, the dimension D of the exposed areas of substrate 610 is small. For example, D can be on the order of 1-100 micrometers, preferably 5-20 micrometers. The exposed areas can be in the form of an array of rounded holes or polygons such as squares. As illustrated in Fig. 6C, carbon nanotubes or other nanostructures are selectively deposited on the exposed Si surfaces of substrate 610 by electrophoresis. In one embodiment, the chemical etched structure is immersed into a carbon nanotube suspension. Contact to the power source is made on the back of surface 610. A metal plate is used as the counter electrode. A bias voltage is also preferably applied to the conductive surface 630 to prevent deposition of carbon nanotubes on the metal surface. Under the applied electrical field, carbon nanotubes will migrate to the exposed surfaces of substrate 610.

For purposes of illustration, the dielectric layer 620 can have a thickness on the order of 1-100 micrometers, preferably 1-10 micrometers.

Figure 7A and 7B show the top view of the etched multi-layer structures formed as described above.

In addition, the electrophoresis method of the present invention can also be utilized to form a patterned deposit of nanostructure-containing material onto a substrate.

Figs. 8A to 8D illustrate one embodiment of this application. According to the illustrated embodiment, a mask 640 is placed on top of a first surface of a substrate 650 before electrophoresis. The area 670 on the surface of substrate 650 where no deposition is intended is blocked by the mask 640, while the areas 660

on the surface of substrate 650 are exposed to the electrophoresis bath through corresponding openings in the mask 640.

The masked substrate is then introduced into a suspension and coated by electrophoresis in a manner consistent with the present invention, as set forth in detail above.

After deposition, the mask 640 is removed from the substrate 650 and a clean patterned structures 680 containing nanostructure-containing material is obtained, as illustrated in Fig. 8D. The dimension(s) and shape(s) of the patterned structures are defined by the openings of the mask 640.

Figures 8A and 8B show the side and the top view of the mask-blocked substrate before electrophoresis. Figure 8C shows the side view of the mask-blocked substrate after electrophoresis. Figure 8D is the side view of the final structures on the substrate.

While the present invention has been described by reference to the above-mentioned embodiments, certain modifications and variations will be evident to those of ordinary skill in the art. Therefore, the present invention is limited only by the scope and spirit of the appended claims.